Model-Based Inquiry and School Science: Creating Connections

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Much has been made in recent years of inquiry approaches to science education and the promise of such instruction to alleviate some of the ills of science education, yet in some ways this construct is still unclear to many in the field. In this paper we explore one view of inquiry in science that is based on the development, use, assessment, and revision of models and related explanations. Because modeling plays a central role in scientific inquiry it should be a prominent feature of students' science education. We present a framework based on this view that can serve as a guide to curriculum development and instructional decision-making with the goal of creating classroom environments that mirror important aspects of scientific practice. Specifically, the framework allows us to emphasize that scientists: engage in inquiry other than controlled experiments, use existing models in their inquiries, engage in inquiry that leads to revised models, use models to construct explanations, use models to unify their understanding, and engage in argumentation. Here, we discuss how these practices can be incorporated into science classrooms and illustrate that discussion with examples from our research classrooms.

In the United States and many other countries there is grave concern about the state of science education. This concern stems from two related issues: first, that many schoolchildren are leaving secondary school without an understanding of even the most fundamental ideas in science and second, that many capable students are not choosing to continue studying science at the college level. When science instruction is incomprehensible and uninspiring it fails the most basic mission of science education. Much has been made in recent years of inquiry approaches to science education and the promise of such instruction to alleviate some of the ills of science education. The current focus on this issue began in the 1990s when scientists and science educators undertook a lengthy process that resulted in the publication of the *National Science Education Standards* (National Research Council [NRC], 1996). Broad in scope, the *NSES* presented an ambitious agenda for far-reaching reform that identified the primacy of inquiry to science and to an education in science. "They [the *NSES*] emphasize a new way of teaching and learning about science that reflects how science itself is done, emphasizing inquiry as a way of achieving knowledge and understanding about the world" (NRC, p. ix).

This vision is still unrealized in many science classrooms (Crawford, 2007). We suggest that perhaps one reason for this is a lingering lack of clarity about what exactly inquiry is in the context of science education and how it contrasts to other approaches. In particular, there is often a conflation of hands-on science with inquiry and while true classroom based inquiry is almost always hands-on, the reverse is not true. We claim that the key in deciding if something is consistent with inquiry is to determine the fidelity between the intellectual work being asked of students and that which might occur in the work of science. Thus, our working definition of inquiry in science education is focused on the process of developing explanations about the natural world through participation in the complex activities of scientific practice. That is, inquiry is the act of systematically investigating and exploring aspects of the natural world in order to develop coherent explanations for how those features of the world work. In this paper we explore this view of inquiry and a framework that has developed from it. Our view and the framework are based on a number of years of classroom-based research and theoretical exploration of the issues facing science educators. The purpose of this paper is to clearly and explicitly delineate ways in which our perspective on inquiry can lead to classroom environments that go beyond mere hands-on work to those which

promote reasoning that is consistent with what scientists actually do.

Situating science teaching in the context of inquiry is not new. Early in the twentieth century, Dewey (1910) called for science to be taught through inquiry experiences and chastised status quo teaching for presenting science as "...so much ready-made knowledge, so much subject-matter of fact and law" (p. 124). Five decades later, one of the 20th century's leading science educators, Schwab (1958) argued that science teaching should focus on how scientific knowledge is created and justified rather than upon a "rhetoric of conclusions"— his phrase for an emphasis on knowledge, independent of an understanding of how that knowledge is produced. Schwab urged that science be taught by inquiry and made it clear that inquiry involves more than familiarity with the formulaic "scientific method" found in K-12 instruction (typified by the steps: problem, hypothesis, experiment, results, conclusion). For Schwab and others, this version of inquiry—beginning as it did with problem and ending with conclusions—was inconsistent with actual scientific practice (Rudolph, 2005). However, despite the efforts of many science educators to incorporate a realistic vision of scientific inquiry into science instruction, little has changed (Crawford, 2007; Windschitl, Thompson, & Braaten, 2008).

Recently though, educators have once again returned to considering what view of inquiry would be appropriate as an underpinning for developing curricula and instruction for K-12 science classrooms (Duschl, Schweingruber, & Shouse, 2007). In some cases the attention to inquiry has been sweeping, lacking in specificity in terms of how classroom practices relate to scientific inquiry writ large, and therefore limited in utility. However, many scholars have come to recognize that scientific inquiry differs among disciplines and that discipline-specific conceptions circumscribe the questions scientists ask as well as the approaches they take when pursuing answers to those questions (Rudolph, 2005). This approach too, has a drawback in that paying too much attention to the specificity of individual scientific practices could result in a view that is so detailed that it also lacks utility.

We argue that a middle ground is essential if inquiry science instruction is to have any hope of being incorporated into classroom practices and more importantly if it is to lead to scientifically literate students who are inspired rather than overwhelmed by science as an intellectual activity. Thus, the framework presented here is in service of this goal: scientific literacy defined as an understanding of the content of science coupled with an understanding of how that knowledge was generated and justified. This has led us to look for commonalities across disciplines, commonalities of purpose that can accommodate uniqueness in approach.

We have found that model-based reasoning is a cornerstone of every discipline to some degree (Derry, 1999; Frigg & Hartmann, 2006; Giere, 1988; see also Gilbert & Boulter, 2000). That is, all scientific disciplines are guided in their inquires by models[1] that scientists use to construct explanations for data and to further explore nature. The development, use, assessment, and revision of models and related explanations play a central role in scientific inquiry and should be a prominent feature of students' science education.

In this paper we present a framework that reflects a model-based inquiry view of science (Figure 1). A benefit of this framework is that it is more realistic than the textbook "scientific method," because it acknowledges the discipline-specificity of inquiry, and yet because the Practice Framework captures aspects of inquiry common to all disciplines it is general enough to be of value in planning curricula and instruction for any school science area. We recognize that many others have called for modeling and model-based inquiry to be incorporated into science education (most recently see Windschitl et al., 2008). However, the Practice Framework is the only curricular framework that we are aware of that shows the relationships between and among models, explanations, phenomena that make up discipline-specific practice.

At the heart of the Practice Framework is the recognition that models are a cornerstone of every science discipline. The significance of models is that they allow scientists to construct explanations for data and to predict patterns in data. The model itself is a set of "set of hypothesized relationships among objects, processes, and events" (Windschitl & Thompson, 2006, p. 796). That is, the model brings together the theoretical objects and the processes they undergo and thus serves as a mechanism that can be used to explain why something in the natural world works the way it does. Typically models are clustered together to form scientific theories (Giere, 1988). For example, evolutionary theory is comprised of a set of models that includes natural selection, genetic drift and various models of speciation that can be used to construct explanations for changes in populations over varying pe-

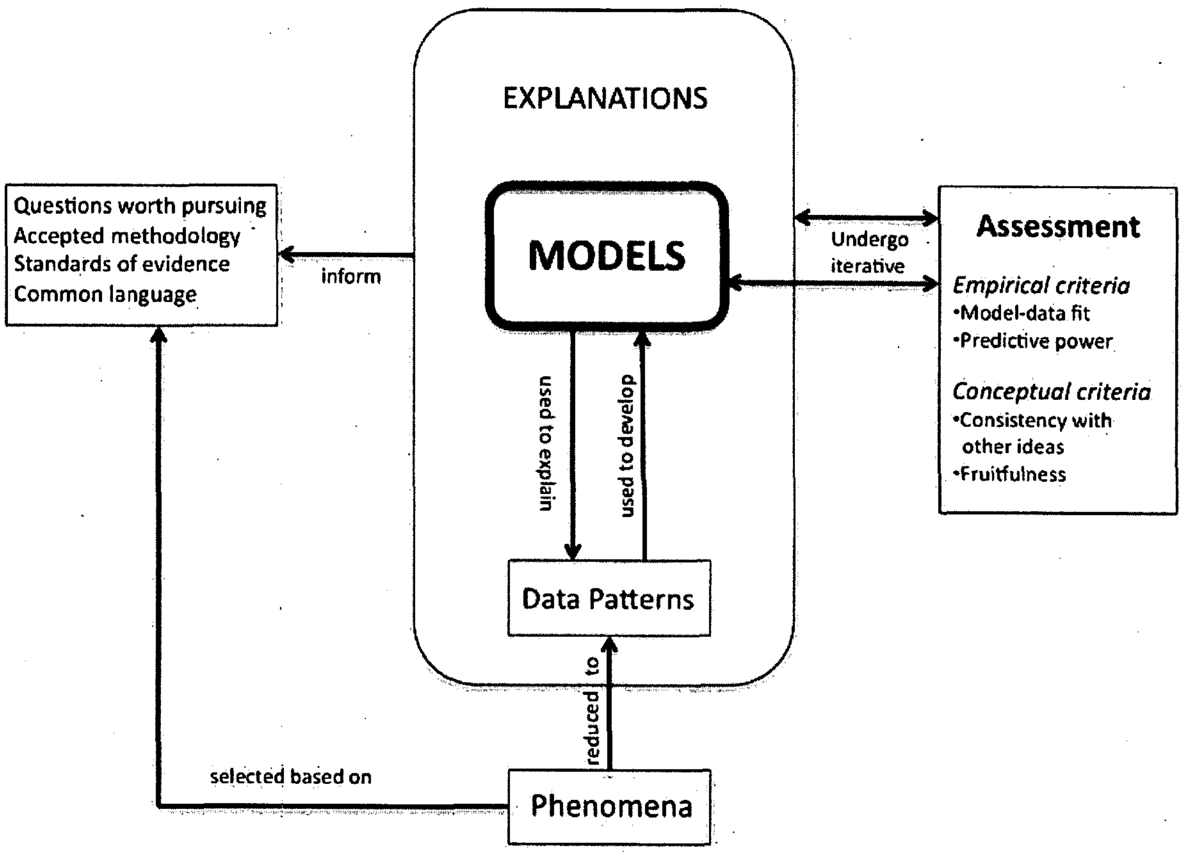

Figure 1. Models are placed at the center of this depiction of discipline-specific practice and highlighted as central with a bold line. The words models and data-patterns are nested within the larger construct of explanation in order to illustrate that explanations are distinct from models, but are structures that bring models to bear on particular data patterns that have been abstracted from phenomena. The right side of the diagram shows that both models and explanations undergo assessment based on conceptual and/or empirical criteria. That is, sometimes the model may be critiqued in isolation, but more often it is an explanation arising from the model that is evaluated leading to an assessment of some aspect of the underlying model (or a re-evaluation of what was considered the relevant data pattern). The left side of the framework is meant to convey that key models and accepted explanations within disciplines are important inputs into the norms of the practice and those norms then are important filters through which practitioners view the world and the phenomena that may need exploration.

riods of time. Because models are so important in science, students should be engaged in reasoning with them and about them.

Towards a Realistic View of Scientific Inquiry

To be considered scientifically literate, students should understand that the methods by which disciplines generate and justify knowledge are diverse and are deployed within practices. Disciplinary practices are comprised of communities of inquirers who are organized around discipline-specific models, language, questions, and reasoning patterns (Kitcher, 1993). The Practice Framework reflects key elements of scientific practice that are useful when designing curricula, making instructional decisions, and assessing students. Of particular value is the emphasis on the role of models in: asking questions, recognizing data patterns, constructing explanations for data, and in providing criteria for judging knowledge claims. In addition, the Practice Framework emphasizes that scientific understanding is embedded within, and inseparable from, the processes by which explanations and models are created, used, assessed and revised.

The Practice Framework represents the products of inquiry (e.g., explanations and models) as embedded within the processes by which they are created and therefore downplays the content-process dichotomy

that is present in some recommendations for science education (see for example *the Science Content Standards for California Public Schools*, California Department of Education, 2003). That is, the Practice Framework places the specific content knowledge in a particular discipline at the center of the process of inquiring into that area. The integrated nature of the Practice Framework makes it useful when designing classrooms where students function as scientists. During the past decade, we have used the Practice Framework to design curricula in genetics, evolutionary biology, Earth-Moon-Sun astronomy, and kinetic molecular theory. In addition, middle and high school teachers with whom we have collaborated have used the Practice Framework to guide instructional decisions (Cartier, Passmore, Stewart, & Willauer, 2005). Focusing on data patterns and models helps the teachers organize tasks and structure interactions as students make sense of complex phenomena and judge competing models and explanations. As a result, students develop understanding as measured by their ability to make sense of novel phenomena (Stewart, Cartier, & Passmore, 2005; Stewart, Passmore, Cartier, Donovan, & Rudolph, 2005).

We have organized this article around six aspects of scientific practice that are brought to life by using the Practice Framework. Although a tool as complex as the Practice Framework has many ideas embedded within it, we've chosen to focus on these six aspects of practice because they are currently underemphasized in many science classrooms. These aspects of practice are also often absent from activities that might be characterized as only hands-on and thus can be used to further explicate the distinction between engaging, hands-on science instruction and approaches that could be characterized as inquiry as well. Several key points are worth making here and will be illustrated with appropriate examples from our research classrooms. Specifically, the framework allows us to emphasize that scientists:

- engage in inquiry other than controlled experiments,
- use existing models in their inquiries,
- engage in inquiry that leads to revised models,
- use models to construct explanations,
- use models to "unify" their understanding, and
- engage in argumentation.

Complete descriptions of the instructional units and results of studies on student understanding can be found in Barton (2001), Cartier and Stewart (2000), Johnson and Stewart (2002), Passmore and Stewart (2002), and Wynne, Stewart and Passmore (2001)[2].

Exploration of Aspects of Scientific Practice

Scientists engage in inquiry other than controlled experiments. While it is true that many scientific disciplines conduct controlled experiments as part of their investigations into the natural world, it is simply not the case that this practice is common across all disciplines or that it should be held up as the exemplar of all science. The ubiquity of experimental science is implied and codified in the textbook "scientific method". When developing model-based inquiry instruction we do include aspects of the "scientific method," particularly hypothesis testing and experimentation. However, we embed them in a conception of inquiry that recognizes that scientists use diverse inquiry methods in order to generate and interpret data as a basis for developing explanations for phenomena.

The textbook view of inquiry, "the scientific method," emphasizes the role of hypotheses but in doing so has shortcomings. For example, hypothesis is followed by experimentation, often narrowly conceived of as controlled experiments. But if there were a universal linear set of steps that scientists follow, hypothesis would be followed by a more general activity, investigation. Why? Because not all scientists conduct controlled experiments. Ethologists (biologists who study animal behavior) generate hypotheses but may not always be able to test them with controlled experiments. It would be impossible to conduct a controlled experiment to choose between the hypotheses that different species of primates display similar predator warning behaviors because of 1) the environment they live in or 2) a common evolutionary history. To choose, ethologists employ a comparative approach in which they observe many species (without experimental manipulation), compare the DNA of those species and examine the fossil record for evidence about the species' history. Comparative methods are common in sciences, such as evolutionary biology and geology, where historical evidence is significant.

Our astronomy curriculum can be used to illustrate classroom inquiry that is not experimental in nature. In classrooms using this curriculum students investigate near-Earth astronomical phenomena such as phases of the moon and eclipses (Barton, 2001). Although students do not conduct controlled experiments, they do test their ideas in systematic ways. They first explore the phenomena and look for patterns. In the case of moon phases this is accomplished through detailed ob-

servations of the moon over several weeks. Once they find a pattern they attempt to explain that pattern by developing a model for how the Earth, moon, and sun must interact to create what we see on Earth. They may use diagrams, globes, balls, and light sources to create their model. They develop an idea and then "see" if they can recreate the phenomenon. This is clearly an investigation where they are moving between conceptual and observational modes, but these actions cannot be called experiments in the traditional sense. Once they have figured out one or more ideas (models) for Earth, moon, sun interactions that can be used to explain the phenomenon, they test those ideas by developing explanations and creating arguments in support of their models.

It is important that we be clear here. We are not saying that controlled experiments are not worthy of emphasis or that they do not make up much of science. Instead, the point here is that they are not all that scientists do and, depending on the discipline, may not play a significant role. Students who are scientifically literate should be able to see that there are a variety of legitimate modes of inquiry within science.

Scientists use existing models in their inquiries. Scientific understanding results when scientists (and students) use models to explain phenomena. For example, simple dominance is a genetic model that is one member of a family of models. It includes objects (i.e., alleles and genes), processes that those objects participate in (segregation and independent assortment), is related to other biological models (e.g., of gene expression and chromosome behavior) and allows scientists and students to explain some pedigree data and to predict the results of crosses.

Unfortunately, the textbook scientific method often fails to acknowledge that hypotheses are embedded in disciplinary traditions that include models and the discipline-specific reasoning patterns that scientists use to pose and pursue problems. Too often the beginning of an inquiry in school science is presented without any background information. In some cases students are asked to generate questions about some observations without any context. If instruction stresses only the textbook scientific method, students may not understand that scientific inquiry is iterative and builds on the results of past inquiries in which scientists used models to generate new knowledge that then is used in future inquiries. To engage in inquiry is to be a member of a community of practitioners who understands the nature of the problems worth solving and who is able to employ the discipline's reasoning patterns to seek solutions to those problems. School science should better reflect the model-based nature of inquiry.

In the genetics curriculum developed by our team, students are introduced to this process in a meaningful way. They begin with a conceptual exploration of meiosis and then they learn about the work of Mendel. As part of this instruction these two models are explicitly linked when students are asked to make sense of Mendel's idea that each individual has two "factors" controlling each trait. As they investigate more genetic phenomena they are able to recognize instances in which Mendel's simple dominance model fails to account for the data and they then revise that model in light of the anomalous data. For example, Mendel's model can only account for traits with two distinct variations and thus traits with more than two variations become anomalous with respect to Mendel's model. Without knowledge of the simple dominance model the students would not be able to recognize that there was something in need of explanation in a particular data set. Moreover, the previous two models (meiosis and simple dominance) constrain the model revision process by circumscribing the problem space in productive ways. For example, students might initially propose a model that postulates 3 alleles per individual for a particular trait. They quickly realize, however, that such a model would be inconsistent with meiosis and therefore the range of ideas they explore is influenced by the scientific models they are working with at the outset of a new exploration (Wynne et al., 2001).

Too often in science classrooms students are presented with key ideas as a set of disassociated facts (Roth et al., 2006). Many times they do not naturally make connections between ideas and they are very seldom asked to do so. Engaging students in model-based inquiry presents an authentic context that requires them to make connections and use one set of ideas to lead them in their investigation of new ideas. This is a much more accurate reflection of what scientists do and has the potential to add coherence to the science curriculum.

Scientists engage in inquiry to develop and revise models. There is inquiry other than testing hypotheses by experimentation or by other equally scientific, but non-experimental methods. Such inquiry occurs when there is no model that accounts for a range of observed phenomena or when models are found to be internally inconsistent, inconsistent with new data, or with other accepted knowledge. When these inconsistencies

occur, the inquiries of some scientists turn from using a model to solve empirical problems to conceptual inquiry aimed at remedying the noted inconsistencies. Inquiries of this kind may require models be constructed anew, abandoned, or more often revised. Take for example the work done by Waston, Crick, and others in developing a model of the DNA molecule. Much was known, from empirical studies, about the attributes such a molecule must have, but little was known about the structure and thus the utility of this information was limited. The breakthrough came when these scientists synthesized information from a number of sources and postulated a structure. Once the model (the double helix structure) was proposed, more empirical work could be undertaken to test it. Such conceptual inquiries—in which scientists examine the coherence of their discipline's accepted knowledge—are significant to science yet, they are rarely represented in science classes. If students view inquiry as only empirical manipulation, they may not value the contributions of conceptual inquiry to science.

We will use the astronomy curriculum to illustrate this point. One of the phenomena that students explore in this course is eclipses. They are presented with data on the frequency of eclipses and are asked to use their understanding of the Earth, moon, sun system to explain the pattern they see in the data. Specifically, they need to explain that eclipses occur in pairs of one lunar and one solar eclipse approximately every six months. Up to this point, the students have already developed a model in which the moon orbits the Earth one time approximately every 28 days and that the direction of the orbit is the same direction as the rotation of the Earth. Most students, however, have not described the planar orientation of this orbit at all and it is this issue that they are forced to confront because of the eclipse data. Many of them quickly realize that the simplest way to avoid having an eclipse during a new or full moon phase is to move the moon out of the Earth-sun orbital plane. At this point their inquiries become largely of the conceptual nature noted above. That is, the students must postulate a mechanism that would allow the moon to be out of the Earth-sun plane most of the time, but cross it at key points. In undertaking this inquiry they are reminded that their ideas must fit with the general principles of physics and that any revisions they make to their model must not jeopardize their ability to explain the data that they had explained previously (moon phases, for example).

Science curricula should provide students with opportunities to experience conceptual inquiry as they develop, use and revise models in response to anomalous data or to contradictions with other accepted models, and to assess those revised models for empirical and conceptual consistency. Conceptual inquiry, while common in science, is rarely introduced in traditional science classrooms.

Scientists use models to construct explanations. It is through the act of constructing explanations that scientists come to understand the natural world. This intimate connection of explanation to understanding should be of interest to science teachers. If students develop and justify explanations then they have participated in science and then have the opportunity to develop metaknowledge of this practice. It is that metaknowledge of how knowledge is generated and justified in science, coupled with the particulars of the major scientific models, that is the hallmark of science literacy.

Scientists pose and seek answers to questions about unique events (why was there a fish kill in Black Earth Creek in the late summer of 2001?) or for patterns in events (why do many members of the Lu family have difficulty digesting dairy products?). Such questions result in answers that take the form of explanations in which a model, or models, is joined with empirical observations (data). In the case of the Lu family this process might involve creating an explanation, using a genetic model such as simple dominance, to explain why some family members have an allergic reaction to dairy products. Alternatively, an explanation might be developed, using evolutionary models, to explain the absence of an enzyme for digesting dairy products in certain populations based on ideas about selective advantage.

Our natural selection curriculum illustrates this point particularly well. In this unit students first explore the natural selection model and its underlying components (such as variation, selective advantage, superfecundity and so on). Once they have a clear understanding of the model they employ it to explain natural phenomena (see Passmore & Stewart, 2002 for a complete description of this curriculum). They are asked to create Darwinian histories of extant organisms by drawing on the tenets of natural selection and information about the organism and its habitat. For example, in one case study they are presented with data related to monarch and viceroy life histories and asked to explain the similarity in color between the two distantly related butterfly species. In crafting their explanations they must

weave together information about the butterflies with their knowledge of the natural selection model. That is, they know that natural selection relies on heritable variation and that in order for a particular trait to become more common in the population it must confer some kind of selective advantage on individuals with that trait. This leads them to consider what evidence they have in their information packets about variation and the environment so that they can make specific claims about the organisms in question and the selective advantage of particular trait variations.

Because model-based explanations are central to science they should occupy a prominent position in school science. Students should be given opportunities to see that the scientific ideas they learn about (the models) are useful in developing explanations for patterns in the natural world. Requiring students to use their knowledge to construct explanations for natural phenomena is quite different from asking them to simply repeat the ideas back on a test. The former is much more relevant to the intellectual enterprise of science than the latter and more likely to lead to understanding of both the content and process of science.

Scientists use models to unify understanding. Scientific disciplines are highly unified because models serve to bring together phenomena and because models are organized into "families" (Giere, 1988). For example, if a researcher were to examine human and fruit fly pedigrees she might observe similar patterns yet, because humans and fruit flies differ in appearance, it may not be obvious to explain the similar patterns with a single model. This is what is possible given Mendel's model of simple dominance (and other genetic models); diverse phenomena are brought together within one explanatory structure.

In addition, a discipline gains coherence because its models fall into model families. For example, students see when looking at pedigrees in the genetics course that there are obvious patterns found in some pedigrees and not others. However, as they engage in the model revision process they see that the models used to explain these diverse pedigree patterns share a 'family resemblance' in that there are some number of alleles in the population of organisms from which the pedigree is constructed, some subset of those alleles occur in each individual, there are certain allele combinations that occur in individuals, and alleles interact with one another in prescribed ways. In this example, classical genetics is 'unified' by bringing seemingly diverse causal models (e.g., simple dominance and multiple alleles) under a single family structure. As a result, students see that genetics has a conceptual and explanatory coherence, rather than being a grab bag of unrelated facts to be committed to memory.

Scientists engage in argumentation. In science and in science classrooms, argumentation is the public face of inquiring, modeling, and explaining. Argumentation is the process by which scientists assess the adequacy of their explanations for data patterns and of the models that they have used to develop those explanations.

Argumentation occurs throughout an inquiry and although it is public in nature it does not require large audiences—it can occur between two individuals throughout an inquiry. When focusing on explanation as a part of argumentation one must be concerned with the consistency of the explanation. Specifically, one must make sure that it does not violate the assumptions of the model that is used in its construction and that it accounts for the phenomena/data at hand. In the model-based inquiry classrooms we have created, argumentation is valued. Across these classrooms one could observe students engaged in a range of the activities including:

- using models to pose questions and to generate data to address those questions
- developing an appropriate language for conversing about models and explanations
- revising causal models in light of anomalous data
- developing explanations that link causal models and data
- assessing models and explanations

The model-based inquiry context allows for multiple entry points into the practice of argumentation. It is important to note, however, that effective argumentation does not come easily to middle school or high school students. They need to be introduced to norms of interactions that allow communities to disagree profitably and they need to develop discipline-specific norms of argumentation. A classroom where argumentation is taken seriously involves more than students making presentations to classmates with only limited interaction. Teachers who are committed to having classrooms function as scientific communities realize that this is a long-term commitment, one that requires careful planning and orchestration. Making scientific arguments involves a deft coordination of data and models resulting in an explanation. Similarly, students who are being persuaded have a significant role—they have to attend to the argument, be aware of the standards for assessing explanations, and be inclined to use

those standards in their interactions with others. (Driver, Newton, & Osborne, 2000)

Summary

We began this article by noting the growing consensus about the value of engaging students in inquiry. We agree that inquiry is important because, in part, we define understanding as the ability to inquire. Further, we have argued that inquiry is a process of developing explanations about the natural world through participation in the complex activities of scientific practice. Thus, scientific knowledge cannot be teased apart from its generation and use, and to engage the activities of scientific practice is key to developing and demonstrating understanding. The complex and elusive nature of scientific understanding creates a significant challenge for educators struggling to identify learning outcomes for students and to develop ways to assess student understanding. For students, understanding science is the ability to function within a particular practice and requires that they couple their knowledge of causal models and the justification for their acceptance with the ability to use that knowledge to make sense of novel phenomena.

Given its consistency with the activities of scientific communities, our Practice Framework is a valuable tool for curriculum designers and teachers and may have implications for science education reform efforts. In the current educational landscape of high stakes testing and accountability, achieving an educational experience for students whereby they begin to see the logic and conceptual consistency of science is crucial. The testing climate has the potential to further fracture the coherence of science education by focusing too much on the acquisition of disparate information, but in fact, a focus on model-based inquiry can help develop coherence in the curriculum and help students develop deeper understanding. Recognizing that understanding in science develops in classrooms inspired by realistic scientific practices may help the science education community create a clear and sophisticated vision of scientific inquiry that can guide curriculum and professional development (Windschitl et al., 2008). The Practice Framework codifies some of the key relationships inherent in such a view. Students deserve an experience in school science that is comprehensible, coherent, and intellectually inspiring and by creating classrooms that mirror important aspects of scientific practice all three of these purposes can be achieved.

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Authors' Notes

The preparation of this manuscript was supported by the National Science Foundation (REC-9972963) and by the Educational Research and Development Centers Program (R305A6007-98), as administered by the Office of Educational Research and Improvement, U.S. Department of Education, and by the Wisconsin Center for Education Research, University of Wisconsin–Madison. The opinions, findings, and conclusions do not necessarily reflect the views of the supporting agencies.

Thanks to the Modeling for Understanding in Science Education (MUSE) group, Andrea Anderson, Keffrelyn Brown, Susan Carpenter, Jana Gearhart, Susan Johnson, and Brian Zoellner, for their contributions of ideas and for their comments on drafts of this paper. Special thanks go to Linda D'Acquisto for her comments on many drafts of this paper.

[1] There are many definitions of models in the science education and science studies literature. For our purposes here we use the following definition: models are sets of ideas that consist of objects and the processes that the objects undergo, or as Windschitl and Thompson (2006) put it, a model as a "set of hypothesized relationships among objects, processes, and events" (p. 796). Models are used to explain and predict patterns in data (e.g., Gregor Mendel's simple dominance model and Charles Darwin's natural selection model are examples of central models in biology).

[2] Instructional materials for the EMS unit and for one in evolutionary biology are available at the MUSE website http://www.wcer.wisc.edu/ncisla/muse/